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Development and Optimization of Wearable Sensors for Vital Signs Monitoring Using the Internet of Things

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Abstract:
As the global elderly population grows, there is an increasing need for reliable and easy to use health monitoring tools that support independent living and reduce strain on healthcare system. This study presents the development of a wearable, Internet of Things (IoT) enabled device designed to monitor vital signs and environmental conditions in real time. The system integrated two low-cost sensors: the MAX30100 for tracking blood oxygen saturation (SpO_2) and heart rate, and the BME680 for measuring temperature, humidity, gas resistance (for VOCs), and air pressure. These sensors were connected to ESP8266 microcontroller that transmitted data through Wi-Fi to a mobile dashboard using the Blynk platform. To improve accuracy, especially during motion, signal processing techniques such as a moving average filter were implemented. The device was tested against commercial health monitoring tools and demonstrated strong performance, with an average error of ±2% for SpO_2 and ±5 BPM for heart rate. It also included threshold-based alerts to notify users or caregivers when readings exceed safe limits. This study contributes to the advancement of affordable, remote health monitoring systems by offering a practical solution that combines physiological and environmental sensing in a compact, user-friendly design. Its potential applications include elderly home care, telehealth services, and mobile health clinics.

Keywords: IoT; Vital signs monitoring; ESP8266; BME680; MAX30100

1. INTRODUCTION

The integration of wearable sensors with the Internet of Things (IoT) has revolutionized healthcare by enabling continuous, real-time monitoring of vital signs (1)**.** These advancements facilitate early detection of health anomalies, improve patient outcomes, and reduce the burden on healthcare systems, particularly in aging populations (2)**.** Wearable devices equipped with sensors like the MAX30100 and BME680 have become instrumental in tracking physiological parameters such as heart rate, blood oxygen saturation, and environmental conditions (3)**.** Despite the progress, challenges persist in ensuring the accuracy, reliability, and energy efficiency of these wearable systems. The MAX30100 sensor, while effective in measuring pulse oximetry and heart rate, can be susceptible to motion artifacts and varying skin tones, affecting data precision (4)**.** Similarly, the BME680 sensor, designed for environmental monitoring, requires meticulous calibration to provide accurate readings of temperature, humidity, and gas concentrations (5)**.** In response to identified clinical gaps, this work proposes a streamlined, energy-efficient wearable monitoring system designed for real-time deployment in non-clinical settings. The objectives include designing an energy-efficient system architecture, implementing robust data processing algorithms, and ensuring seamless IoT integration for real-time data transmission and analysis.

To address these gaps, this study develops a wearable IoT-enabled health monitoring system with four primary objectives. The research focuses on designing and integrating low-cost, high-performance sensors, specifically the MAX30100 for blood oxygen saturation (SpO_2) and heart rate measurement and the BME680 for monitoring environmental parameters, into a unified and compact platform. The system leverages IoT technologies through the ESP8266 microcontroller and the Blynk interface to enable real-time data transmission, visualization, and cloud-based storage. To enhance signal accuracy, advanced filtering techniques such as moving average filters are employed to minimize noise and motion artifacts. Additionally, an automated threshold-based alert mechanism is incorporated to notify caregivers or healthcare providers when critical physiological parameters deviate from their normal ranges, thereby improving responsiveness and overall system reliability.

The scope of this research focuses on creating a compact, wearable prototype capable of monitoring vital signs (heart rate, SpO_2) and environmental parameters, temperature, humidity, gas resistance (for VOCs), and pressure using a unified IoT platform. The system leverages Wi-Fi connectivity and the Blynk interface for real-time accessibility, ensuring seamless

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data acquisition, transmission, and storage. Validation is conducted through controlled experiments and comparisons with commercial devices (e.g., pulse oximeters), demonstrating clinical relevance with ±2% SpO_2 error and ±5 BPM heart rate accuracy. Additionally, the study addresses challenges in power efficiency, sensor calibration, and ergonomic design for elderly care applications, emphasizing the integration of physiological and environmental data to provide a holistic health overview.This device reflects the growing trend toward decentralized, IoT-driven healthcare solutions, particularly in personalized monitoring, offering a cost-effective solution for remote patient monitoring. By combining real-time physiological and environmental insights, the system enhances proactive healthcare interventions, reduces hospitalization risks, and improves the quality of life for elderly individuals. Its user-friendly design, low-power consumption, and automated alert notifications position it as a pivotal advancement in wearable health technologies, addressing both technical and usability challenges in existing systems (6).

The evolution of wearable sensors and IoT-based health monitoring systems has garnered significant attention in recent years, with numerous studies exploring various aspects of physiological and environmental sensing. Early efforts, such as those by Hong *et al.* (7), focused on smartphone-integrated wearable systems for real-time tracking of SpO_2 and heart rate in cardiac patients. While this work provided foundational insights, it was limited to physiological metrics and did not account for environmental influences, which are increasingly recognized as critical for holistic health assessment. Similarly, Hasan *et al.* (8) proposed a low-cost IoT framework using the ESP32 microcontroller and the MQTT protocol for vital sign monitoring. However, their system excluded environmental parameter sensing and lacked features tailored for usability in elderly care applications. Further developments by Sudha *et al.* (9) emphasized IoT-enabled remote monitoring of physiological parameters, including heart rate and SpO_2, with a strong focus on data transmission and wireless communication. Nonetheless, their system was restricted to single parameter monitoring and overlooked key factors such as sensor calibration, signal stability, and power optimization limitations that impact long-term usage. In contrast, studies focused on environmental sensing, such as Lasomsri *et al.* (10), used the BME680 sensor for indoor air quality (IAQ) monitoring in hospitals. While the study effectively demonstrated the environmental sensing performance of the BME680, its lack of physiological data integration limits real-world healthcare applications.

Zakaria *et al.* (11) expanded this direction by developing a wireless IoT-based air quality system with real-time alerts. While innovative, the solution centered exclusively on environmental data and lacked vital monitoring, limiting its clinical impact. Additional work have leveraged platforms like Arduino and ZigBee to visualize environmental parameters and indoor lighting levels (12, 13). These studies, though strong in data delivery, did not incorporate any physiological sensing capabilities. Most recently, Yoganapriya *et al.* (14) developed an IoT-enabled system for COVID-19 patients to monitor SpO_2 and heart rate. However, the system did not factor in environmental variables, which are particularly relevant in respiratory conditions. Taken together, these studies highlight a critical gap: few platforms offer a unified solution that monitors both environmental and physiological metrics in real time. Furthermore, many existing solutions lack automated alerts, energy efficiency, and ergonomic design, making them less suitable for continuous use in elderly care or mobile health settings.

2. METHODOLOGY

2.1 System Overview

The suggested wearable system integrates physiological and environmental monitoring into a small IoT-based device designed for real-time healthcare use. The ESP8266 Mini (NodeMCU) microcontroller manages data from two sensors: the MAX30100 measures blood oxygen saturation (SpO_2) and heart rate, and the BME680 detects environmental variables like temperature, humidity, gas resistance (for VOCs), and pressure. The embedded sensors communicate with the microcontroller using the I2C communication protocol, ensuring efficient data collecting. Processed data is communicated over Wi-Fi to the Blynk IoT platform, where consumers and healthcare practitioners can benefit from real-time monitoring and alerts, Additionally, readings are displayed locally on an OLED screen embedded in the device, enhancing usability in low-connectivity settings. The overall system structure is detailed in Figure 1, which outlines data acquisition, signal flow, and cloud communication pathways.

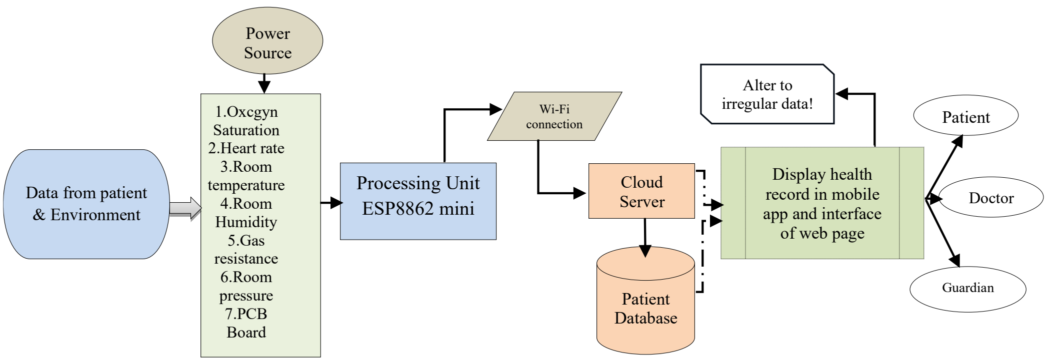

Figure 1. Block diagram of the system.

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2.2 Hardware Components and Specifications

The proposed system hardware configuration is based on a low-power, compact design appropriate for wearable applications. The system relies on the ESP8266 NodeMCU microcontroller, which has Wi-Fi capabilities, low power consumption, and supports I²C communication protocols. The device connects to two important sensors: the MAX30100 for physiological monitoring (SpO_2 and heart rate) and the BME680 for environmental sensing (temperature, humidity, VOCs, pressure). The I²C protocol connects these sensors, simplifying wiring and allowing for fast data collecting. The complete arrangement is built on a bespoke printed circuit board (PCB), which includes power input connectors, an OLED display, and sensor modules. The circuit design was completed using Proteus software and physically realized on a compact PCB that fits within a 3D-printed enclosure developed using Fusion 360. This enclosure, measuring 50 mm × 40 mm × 30 mm, was specifically engineered to ensure portability, mechanical stability, and ergonomic comfort. The exploded view of the casing and its internal sensor layout is illustrated in Figure 2, offering a visual representation of the modular mechanical design.

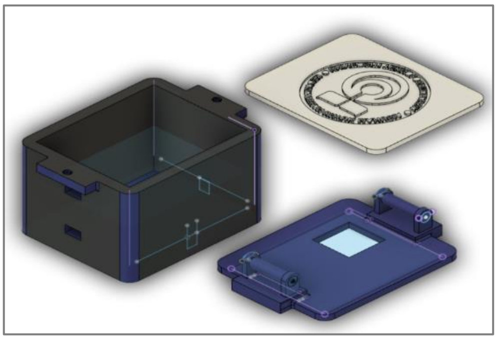

Figure 2. Finalized 3D rendering of the portable design concept.

Power is supplied by a 110 mAh lithium-ion rechargeable battery, delivering 3.7 V DC, with charging managed through an onboard TP4056 module to enable USB-based power replenishment. The complete PCB wiring and electrical integration, including sensor interfacing and power connections, are depicted in Figure 3, which highlights the hardware's internal configuration and component distribution. This design provides the foundation for a wearable, real-time health monitoring device that is both energy-efficient and field-deployable.

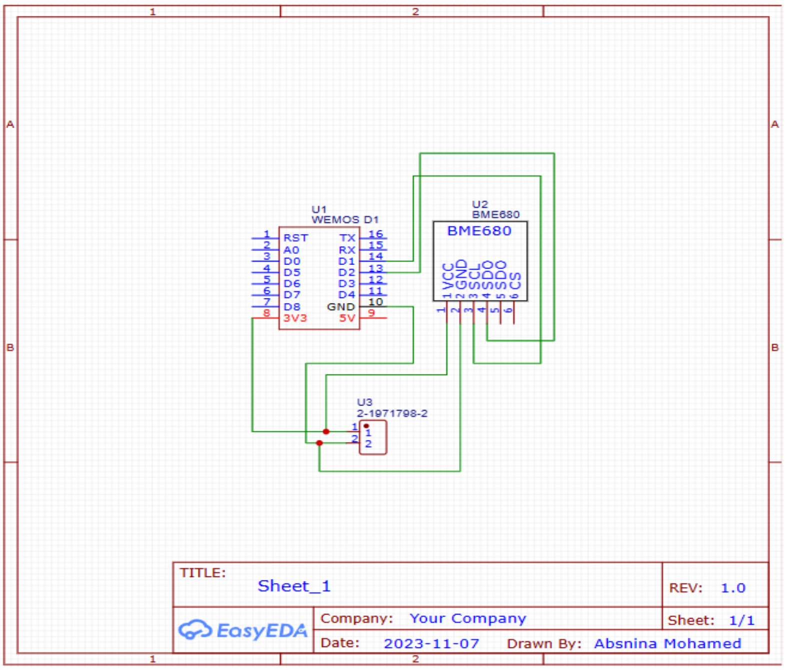

Figure 3. Electrical circuit of printed circuit board (PCB).

2.2.1 MAX30100 (SpO_2 and Heart Rate)

The MAX30100 sensor integrates red and infrared LEDs with a photodetector, optimized optics, and low-noise analog signal processing to measure blood oxygen saturation (SpO_2) and heart rate via photoplethysmography (PPG). It operates at 1.8V internally and communicates with the ESP8266 using I2C at 3.3V logic levels. The device includes ambient light rejection and configurable sampling rates, making it well-suited for wearable applications.

2.2.2 BME680 (Air Quality & Environment)

The BME680, manufactured by Bosch Sensortec, is a multi-functional sensor capable of measuring temperature, humidity, pressure, and gas resistance (used to estimate VOC levels) (Table 1). It operates between 1.8V to 3.6V, also using I2C for communication. The sensor was calibrated using readings from a commercial HTC-2 hygrometer to correct for offsets and align with real-world conditions. Additionally, Bosch's BSEC software library was implemented to enhance gas resistance data interpretation by applying internal compensation algorithms.

Table 1. Sensor's specifications used in the system.

Sensor	Parameter	Range / Accuracy	Communication	Power Supply
MAX30100	SpO_2 (%)	0–100% ±2%	I2C	1.8V / 3.3V I/O
	Heart Rate (BPM)	30–240 BPM ±1 BPM	I2C	1.8V / 3.3V I/O
BME680	Temperature (°C)	-40 to +85 ±0.5°C	I2C	1.8–3.6V
	Humidity (%RH)	0–100% ±3%	I2C	1.8–3.6V
	Pressure (hPa)	300–1100 ±1 hPa	I2C	1.8–3.6V
	Gas (VOC)	Variable resistance value	I2C (via BSEC)	1.8–3.6V

2.3 System Architecture and Data Flow

To ensure smooth and reliable data collection and communication, a well-structured system architecture was developed, as shown in Figure 4. The process starts with capturing both physiological and environmental data using two key sensors: the MAX30100 for heart rate and SpO_2, and the BME680 for temperature, humidity, air pressure, and gas levels. These raw signals are first processed by the ESP8266 NodeMCU microcontroller, which applies basic filtering like a moving average filter to reduce noise, correct signal drift, and improve the accuracy of the readings. Once cleaned, the data is sent wirelessly via Wi-Fi using the MQTT protocol to the Blynk IoT platform. Blynk serves two important roles: it acts as a cloud-based storage system for the data and provides a user-friendly dashboard accessible through smartphones or web browsers. Users can view real-time updates, track trends, and access vital health insights with ease. Importantly, the system includes a built-in alert feature that sends instant notifications to users or caregivers if any reading—whether physiological or environmental crosses a set safety threshold. This feedback loop helps users respond quickly to potential health issues, making the system both proactive and responsive. As illustrated in Figure 4, the complete flow from sensing to real-time alerts demonstrates a robust and practical architecture, well-suited for real-world wearable health monitoring applications. The sampling time for data acquisition and storage was set to 2 seconds (0.5 Hz) per reading for each parameter, ensuring consistent real-time monitoring without overloading the data buffer.

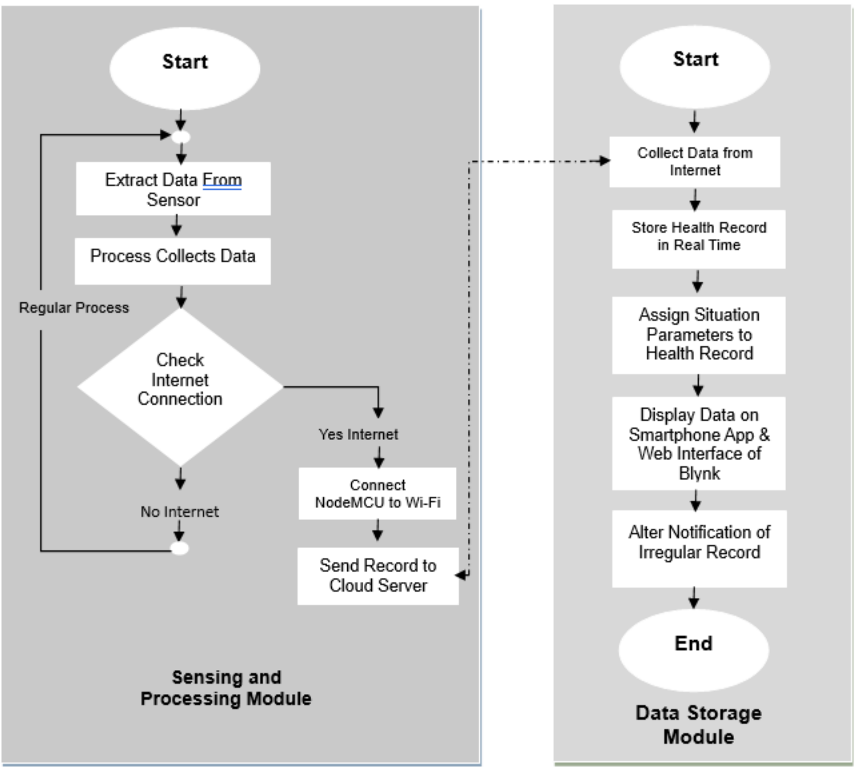

Figure 4. Flowchart of the complete system.

3. RESULTS AND DISCUSSION

3.1 Accuracy and Reliability of Vital Sign Measurements

To assess how accurate the wearable system really is, we compared its performance to a standard fingertip pulse oximeter (model LK87). Specifically, we focused on the MAX30100 sensor's ability to measure blood oxygen saturation (SpO_2) and heart rate (BPM). The test involved eight healthy volunteers, aged between 22 and 29, who were monitored under calm, resting conditions. While the wearable device was placed on the index and middle fingers, the reference device was worn on the opposite hand to ensure a fair comparison. The results were encouraging: the MAX30100 delivered a mean absolute error of just ±1.03% for SpO_2 and ±1.88 BPM for heart rate when compared with the commercial device well within clinically accepted ranges for non-invasive health monitoring. To improve consistency, we implemented a moving average filter directly into the firmware of the ESP8266 microcontroller, which helped smooth out random fluctuations and motion-induced noise, especially helpful during small hand movements. We also designed custom stretchable finger sleeves to hold the sensor firmly in place. This not only ensured good contact with the skin but also enhanced the accuracy of the optical readings by reducing signal errors caused by shifting or poor placement.

Figure 5 shows a real-time view of how the system tracks SpO_2 and heart rate over time. The x-axis is labeled as Time (hh:mm PM), and the y-axis is labeled as Measurement Value (SpO_2 %, Heart Rate BPM) to clearly distinguish both parameters. The graph illustrates the device's ability to maintain stable readings when the user is still, while also showing typical signal disturbances caused by movement or finger adjustments. The consistent performance during resting states highlights the reliability of the system for continuous, real-time physiological monitoring. A comprehensive comparison of the system's output with medical-grade reference values is summarized in Table 2, which presents side-by-side observed and actual readings for each participant. The table also includes calculated error percentages and overall accuracy metrics, reinforcing the validity of the system for use in wearable healthcare applications. The moving average filter used a 5-point window, where each new data point was averaged with the four preceding values. This simple smoothing algorithm effectively reduced random fluctuations and improved signal stability without introducing significant delay.

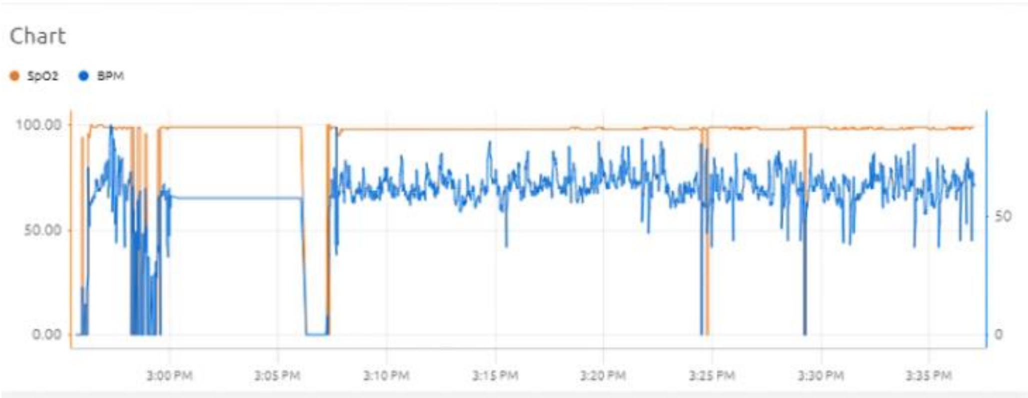

Figure 5. Physiological parameter trends as measured by MAX30100 sensor.

Table 2. Accuracy comparison between MAX30100 sensor and medical-grade reference.

No.	SpO_2 (%)		Heart Rate (BPM)	
	Observed	Actual	Observed	Actual
1	96	96	76	79
2	96	95	83	81
3	98	97	106	106
4	97	99	100	98
5	98	96	95	96
6	97	97	57	56
7	98	97	85	84
8	99	98	79	76
Mean absolute error (%)	1.03 %		1.88%	
Measurement accuracy (%)	98.97%		98.12%	

3.2 Environmental Data Trends and Interpretation

To validate the environmental monitoring capabilities of the BME680 sensor, tests were conducted in three distinct indoor environments: a refrigerator (low temperature, enclosed air), an air-conditioned room (controlled temperature and humidity), and a non-air-conditioned room (higher ambient heat and humidity). The sensor monitored temperature, humidity, and gas resistance (a proxy for VOC concentration and air quality), providing a comprehensive environmental profile for each setting.

Temperature values showed a sharp decline in the refrigerator, as expected, and remained stable in both indoor rooms. Humidity was significantly higher in the non-air-conditioned environment due to the lack of dehumidification, while the air-conditioned room showed moderate and steady readings. The gas resistance values spiked in the enclosed fridge due to the accumulation of gases in a confined space, illustrating the BME680's sensitivity to changes in air quality.

These results confirm the system's effectiveness in detecting subtle environmental variations, making it well-suited for indoor air quality tracking in personal health contexts. The trends across these conditions are depicted in Figure 6, which visualizes the variation in sensor readings under the different test environments. The x-axis is labeled as Time (hh:mm PM) to indicate the progression of data collection throughout the experiment, while the y-axis is labeled as Environmental Parameters (Temperature °C, Humidity %, Gas Resistance kΩ, and Air Pressure hPa) to clearly represent each measured variable. These enhanced labels improve readability and help distinguish between the different environmental parameters, allowing for clearer interpretation of the sensor's performance across varying indoor conditions.

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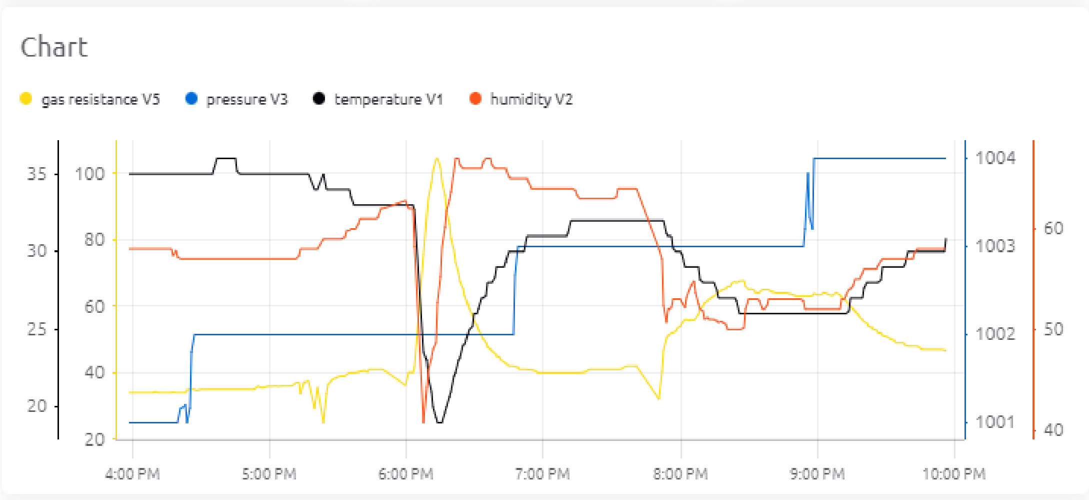

Figure 6. Environmental sensor readings across test locations (temperature, humidity, gas resistance (for VOCs), and air pressure).

3.3 Comparative Performance with Existing Systems

Table 3 illustrates the comparative performance between our proposed system and other existing wearable or IoT-based health monitoring systems. To test how well the BME680 sensor could monitor environmental conditions, we placed it in three very different indoor settings: inside a refrigerator (cold and enclosed), an air-conditioned room (cool and regulated), and a non-air-conditioned room (warm with higher humidity). The sensor continuously tracked temperature, humidity, and gas resistance (for VOCs), the latter serving as an indicator of volatile organic compounds (VOCs) and overall air quality. As expected, temperature readings dropped sharply in the refrigerator and remained steady in the two room environments. When it came to humidity, the non-air-conditioned room recorded the highest levels, reflecting the absence of dehumidification, while the air-conditioned space showed lower, more stable humidity. Interestingly, gas resistance values spiked inside the fridge, likely due to the build-up of gases in the small, enclosed space, demonstrating the sensor's sensitivity to changing air quality (12, 15, 16). These findings show that the system can effectively pick up subtle shifts in indoor environmental conditions, making it a useful tool for personal air quality monitoring, particularly in home or healthcare settings. Figure 6 illustrates these results clearly, showing how the sensor responded differently in each environment and highlighting its potential for real-world use.

Table 3. Comparative performance of the proposed system with existing IoT-based health monitoring solutions.

Ref	MCU	Hardware Components	Architecture	Connectivity	Data access
Dinesh *et al.* (16)	Arduino and ESP8266.	Temperature, heart rate, and SpO_2 level.	IoT	Wi-Fi	IoT cloud-based server.
Darmawan *et al.*(17)	ESP8266.	Pulse oximeter, optional display	IoT	Wi-Fi	Real-time cloud dashboard.
Yoganapriya *et al.* (14)	ESP8266.	Vital signs sensors, SpO_2, and BPM.	IoT	Wi-Fi	Cloud-based Blynk server.

Ref	MCU	Hardware Components	Architecture	Connectivity	Data access
Wang *et al.* (12)	Arduino	Temperature, relative humidity, and CO_2.	WSN	ZigBee	Desktop app.
Salamone *et al.* (15)	Arduino UNO	Temperature and relative humidity.	IoT	ZigBee/BLE	Mobile and web page interface.
Smith and Li (18)	Arduino UNO and Arduino Pro Mini	Temperature, relative humidity, and CO_2.	Wireless	Bluetooth, Wi-Fi.	Cloud storage, access via AirSniffer App).
Our Proposed System	ESP8266 mini	Heart rate, SpO_2, room temperature, humidity, pressure, and gas resistance.	IoT	Wi-Fi	Blynk web page and mobile application.

3.4 Signal Limitations, Error Sources, and Mitigation Strategies

While the proposed system showed strong overall reliability, several technical challenges came to light during testing, especially related to motion sensitivity and environmental variability. For the MAX30100 sensor, one of the main issues was dealing with noise caused by user movement. Even small hand motions were enough to distort the photoplethysmography (PPG) signal, leading to sudden spikes or unstable readings. In some cases, if the sensor shifted or lost proper skin contact, the signal would drop out entirely. Bright ambient lighting also posed a problem, as it could leak into the photodetector and interfere with the optical measurements, further reducing accuracy. The BME680 environmental sensor had its own set of limitations. It reacted sensitively to sudden temperature or humidity changes, and over time, airborne particles could affect its performance, leading to sensor drift. This made it harder to maintain stable and accurate air quality readings. Additionally, its gas resistance output used to estimate VOC levels could sometimes be influenced by unrelated factors like airflow patterns or how close the sensor was to an enclosure or surface. To tackle these issues, both hardware tweaks and software improvements were introduced.

For the MAX30100, a custom stretchable finger sleeve was designed to keep the sensor stable and in constant contact with the skin, which significantly reduced motion-related disturbances. On the software side, we implemented a moving average filter directly on the ESP8266 microcontroller. This lightweight signal processing step had a noticeable impact: the standard deviation for SpO_2 readings dropped from ±2.4% to just ±1.03%, and heart rate error margins improved from ±4.9 BPM to ±1.88 BPM. For the BME680, we integrated Bosch's BSEC (Bosch Software Environmental Cluster) library, which provided built-in compensation for fluctuations in temperature and humidity. It also applied long-term calibration for the gas resistance sensor, helping to correct drift and improve the accuracy of VOC readings over time.

These combined solutions significantly improved data stability and measurement confidence. Table 4 summarizes the key sources of error and the corrective strategies we applied, offering a roadmap for future improvements in wearable health monitoring systems.

Table 4. Summary of error sources and corresponding mitigation strategies.

Sensor	Error Source	Description	Correction Strategy
MAX30100	Motion artifacts	Movement causes signal distortion in PPG readings.	Implemented a moving average filter; finger sleeve for stabilization.
	Poor sensor placement	Inconsistent skin contact reduces signal quality.	Designed a flexible mount to ensure constant placement.
	Ambient light interference	External light leaks into a photodetector.	Enclosed sensor casing to block ambient light.
BME680	Environmental instability	Rapid temperature/humidity changes affect gas sensor stability.	Averaging of multiple readings; filtered baseline correction.
	Sensor drift	Long-term exposure to pollutants degrades sensitivity.	Periodic recalibration using reference sensors.
	VOC interpretation variability	VOC response is nonlinear and context dependent.	Used the BSEC library for temperature/humidity compensation and AI mapping.

The evaluation of the developed wearable health monitoring system confirmed its ability to deliver accurate, real-time measurements of both physiological and environmental parameters, demonstrating strong performance in multiple testing scenarios. Specifically, the MAX30100 sensor provided SpO_2 and heart rate measurements with mean deviations of ±1.03% and ±1.88 BPM, respectively, which fall well within clinically accepted tolerances for non-critical care use. This indicates the system's suitability for home-based health applications, telemedicine, and continuous patient tracking outside of clinical settings. In parallel, the BME680 sensor effectively captured environmental metrics, including temperature, humidity, and gas resistance as a proxy for air quality, and responded sensitively to changes across different indoor environments. The device showed particular strength in detecting variability in enclosed or poorly ventilated spaces, making it valuable for users with respiratory sensitivities. Critically, calibration using commercial reference devices significantly improved the fidelity of the readings, particularly under diverse environmental conditions, which aligned raw sensor outputs with commercial-grade benchmark devices, enhancing reliability under real-world conditions. Notably, the system's multimodal sensing architecture, merging physiological and environmental monitoring in a single wearable unit, stands out as a significant innovation, providing a more holistic health perspective than many existing single-parameter systems.

Furthermore, the integration of dual wireless communication (Wi-Fi and Bluetooth) and the use of the Blynk IoT platform enabled seamless data transmission, visualization, and real-time health alerts via email notifications when abnormal values were detected. However, the system is not without limitations. The MAX30100 sensor remains susceptible to motion artifacts and alignment issues during movement, which may compromise signal accuracy. Likewise, gas readings from the BME680 can drift over time and require periodic recalibration, especially in dynamic environments. Battery performance also presents a constraint, as the device currently supports only 12 hours of operation before recharging is necessary, which limits long-term usability. While pilot tests confirmed the system’s functionality and accuracy, further clinical validation across diverse populations and extended usage scenarios is essential. To improve deployment viability, it is recommended that future versions enhance ergonomic casing design, minimize light interference, and support dual-mode wireless connectivity. Additionally, integrating edge computing functions such as on-device anomaly detection can reduce latency and reliance on cloud services. Power efficiency should also be prioritized, potentially through ultra-low-power microcontrollers or solar-assisted charging, especially for applications in remote or underserved regions. Together, these improvements are expected to make the system more robust, energy-efficient, and suitable for deployment in real-world scenarios.

4. CONCLUSION

In this study, we developed and validated a wearable system that reliably monitors both physiological and environmental parameters that integrating both physiological and environmental sensing into a single, compact IoT-enabled platform. The device combines the MAX30100 sensor for real-time SpO_2 and heart rate measurement with the BME680 sensor for capturing environmental parameters such as temperature, humidity, and gas resistance (for VOCs). Built on the ESP8266 microcontroller and supported by a mobile interface using the Blynk IoT platform, the system enables seamless real-time data acquisition, wireless transmission, and visualization. With additional features such as threshold-based auto-alerts and onboard display, the system offers a reliable, user-friendly, and cost-effective solution for personal and remote health monitoring. Its successful validation against commercial-grade instruments, adherence to clinical error thresholds, and modular low-power architecture highlight its suitability for use in resource-constrained and home-care environments. Moreover, the system design allows for easy scalability and potential commercial deployment, particularly in telemedicine platforms, eldercare services, and mobile health applications.

AUTHORSHIP CONTRIBUTION STATEMENT

Abusnina M. Mukhtar: conceptualization, system design, hardware integration, software implementation, data acquisition, writing - original draft. Mohd Riduan Mohamad: supervision, validation, method, writing - review & editing.

DATA AVAILABILITY

The data supporting the findings of this study, including sensor logs, calibration datasets, and comparative test results, are available upon reasonable request. No proprietary or restricted datasets were used.

AI DECLARATION

No content generated by AI technologies has been used.

DECLARATION OF COMPETING INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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